Proceedings of the ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2019
June 9-14, 2019, Glasgow, Scotland, UK

OMAE2019-95459

THREE-DIMENSIONAL NUMERICAL SIMULATIONS OF SEVERE GAS-LIQUID SLUGGING FLOWS IN S-SHAPED RISER

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ABSTRACT
S-shaped riser may be used for connecting a subsea well and floating platform for the multiphase oil-gas flow transportation. A buoyancy module is installed in the longitudinal direction of the riser section enabling a hog and sag bend arrangement. This design offers a solution to decouple motion from the boundaries and lower the riser stresses. There is an increasing tendency to implement S-shaped risers for offshore platforms operating in deep waters or harsh environments. However, a generic S shape may cause a terrain-induced, severe slugging under certain practical operational/geometrical conditions and flow rates. This phenomenon leads to unstable and intermittent slug flows creating fluctuations of pressure, fluid fraction and velocity components. In this paper, the flow pattern characteristics and formation process of a severe slugging in an S-shaped rigid riser transporting the liquid-gas flows are studied using 3-D computational fluid dynamics simulations based on a finite volume method. Numerical results are validated by comparing with experimental results in the literature. Severe slugging behaviors are presented and discussed.

1. INTRODUCTION
Among several slug flow regimes, a terrain-induced slug flow is caused by the undulated or wave geometry of the subsea riser pipe. This is what normally classified as a severe slugging causing a large pressure, flow variation and a large amount of liquids surging out of the riser pipe outlet. This unstable flow phenomenon is one of the major flow assurance problems in the multiphase liquid-gas flow transportation system. Eventually, the severe slugging could damage the downstream processing equipment such as a separator, increase the pipeline wall stress due to the fluctuating fluid pressure forces, reduce the plant productivity, and shorten the platform design life.

The severe slugging has been defined though various research and experimental studies [1]–[13]. This phenomenon occurs in pipelines with low gas and liquid flow rates due to the liquid static head accumulation rate being greater than the gas growth rate. Previous studies have proposed some conditions for a severe slugging [2], which is typically triggered by the liquid accumulation blocking the gas flows where the pipeline slope changes from a negative to positive angle.

The severe slugging identified in [2] was characterized by the occurrence of liquid slugs that are greater than or equal to the riser length during the cycle. Schmidt [2] suggested that the conditions for a severe slugging require a negatively inclined and stratified flow in the pipeline before the riser base and the hydrostatic head accumulation speed being faster than the gas flow increasing rate, as a maximum pressure at the riser base is equivalent to the riser total height. Schmidt et al. [9] further described a severe slugging cycle in a flexible riser by having a (i) liquid buildup generating the liquid slug at the riser base, (ii) slug production accumulating the pipe-riser-generated slug throughout the vertical riser up and into the outlet separator, (iii) gas bubble penetration from the pipeline into and up the riser part, (iv) gas blowdown and liquid fall back, entailing a blowdown of pipeline gas into the separator.

From the classification defined by Wordsworth et al [14], the severe slugging in a pipeline-riser system is divided into three types. Severe Slugging Type I (SS-I) occurs at a low gas and liquid flow rate. It has a riser becoming full of liquid, so the liquid slug length is greater or equal than one riser length during cycle. As a result, the maximum pipeline pressure is equal to the hydrostatic pressure of the riser height. If the gas flow rate increases from the SS-I, more gas bubbles penetrate through the riser before the liquid slug reaches to the top of the riser. Hence, the maximum pressure and its amplitudes are smaller than those of SS-I. It has some more irregular flow oscillations. This type of severe slugging has a shorter slug length than the height of the riser and often has intermittent unstable oscillations. This is classified as Severe Slugging Type II (SS-II). In the Severe Slugging Type III regime (SS-III), the liquid cannot accumulate completely the pipe cross section at the bottom as a consequence of the continuous gas penetration into the bottom riser. This regime shows a smaller cyclic period and pressure amplitudes compare to previous SS-I and SS-II. With greater high gas and liquid flow rates from SS-III, a continuous gas penetration occurs at the riser section. Consequently, the flow regime enters the oscillation flow region. Other experimental investigations also captured the characteristics of SS-I, SS-II, SS-III and oscillation flow. The pressure, liquid holdup at the riser base and other flow characteristics over the entire riser during a severe slugging were measured. It corresponded well to the description given by Schmidt et al. [9] and Taitel [1].

Tin [15] presented experimental results classifying stable and unstable severe slugging flows and behaviors in curved risers. Three different configurations were considered: free-hanging catenary, Lazy S and Steep S risers. Flow regimes in the S-shaped riser were particularly classified to be the same as those describing a vertical pipe and catenary riser. Experiments by Montgomery [16] and Das [17] were also carried out with variable air-water two-phase flows in an S-shaped riser. The pipeline section had a total length of 57.4m and inclination angle at -2° to the horizontal line. The lazy-S configuration had a total height of 9.98m and length of 18m. From their tests, the characteristics and criterion for the severe slugging (SS-I, SS-II, SS-III and oscillation flow) were captured and compared. The pressure difference, liquid holdup at the riser base and other flow characteristics over the riser during the severe slugging were measured according to the description given by Schmidt et al. [9] and Taitel [1].

The above-mentioned studies reveal a similar severe slugging process developing in an S-shaped riser showing the (1) liquid accumulate at the riser base, (2) the liquid build up at the lower and upper riser sections, (3) the bubble penetration and slug generation through the outlet, and (4) the gas blow down.

Several numerical analyses have been performed for a vertical riser by using a simplified one-dimensional transient model. However, these one-dimensionally approximated studies could not illustrate details and deeper views of actual flow fields and behaviors along the riser length. Nevertheless, there have been only a limited number of studies based on three-dimensional CFD simulations. To the best of the authors' knowledge, numerical simulations of a severe slugging in an S-shaped riser configuration is very lacking. In the study published by Jia [18], three-dimensional CFD study of the Eulerian-Eulerian multiphase flow and a two-way fluid structure interaction with computational structural dynamics in a subsea jumper was performed to identify features of a flow-induced vibration for given initial and boundary conditions. This study included a horizontal pipeline of 27ft length for the jumper and the vertical section with double U bend curves. Pulsatile gas and liquid two-phase flows entering the pipe were configured as a user-defined inlet condition. Lu et al. [19] also carried out similar CFD study for understanding a flow-induced vibration in the subsea jumper with a 80ft long and 5.6-inch internal diameter. More recently, such pulsatile slug flows in a subsea jumper have been considered by Kim and Srinil [20] who showed 3-D numerical CFD simulation results with varying flow rates.

The aim of this paper is to model and investigate the multiphase severe slugging liquid-gas flows in an S-shaped rigid riser by performing 3-D CFD simulations. Numerical simulations are presented, in terms of the volumetric fraction, pressure and liquid holdup, to highlight some details of complex flow behaviors and characteristics of a severe slugging process, in comparison with experimental results in the literature. The paper ends with some key conclusions.

2. NUMERICAL METHODOLOGY

A pressure-based transient simulation was performed using ANSYS Fluent V18.1. The Volume of Fluid (VOF) multiphase model was applied to track the gas (air) and liquid (water) two-phase interface. The governing equations of VOF model were solved by an implicit scheme, with a sharp interface modeling option enabling an interfacial anti-diffusion treatment.

Table 1. Model Setup for Numerical Simulations

Model	Setup	
Solver	Pressure Based, Transient	
Multiphase Model	Volume of Fluid (VOF) Model	
Turbulence Model	k–ω SST RANS Turbulence Model	
Pressure-Velocity Coupling	PISO Scheme	
VOF Interface Tracking	Compressive	
Spatial Discretization	Gradient (Least Squares Cell base) Pressure (PRESTO!) Volume Fraction (Compressive) Second Order Upwind Scheme Density, Momentum, Energy, Turbulent Kinetic Energy, Specific Dissipation Rate	
Under Relaxation Factor (URF)	Pressure	0.3
	Density	1
	Body Forces	1
	Momentum	1
	Volume Fraction	0.5
	Turbulent Kinetic Energy	0.5
	Specific Dissipation Rate	0.5
	Turbulent Viscosity	0.5

The k-omega (k–ω) turbulence with the Shear Stress Transport (SST) model was employed both in the near wall region and the far region from the pipe walls. This hybrid k–ω SST scheme combines the Wilcox k-ω and k-ε models, enabling a more

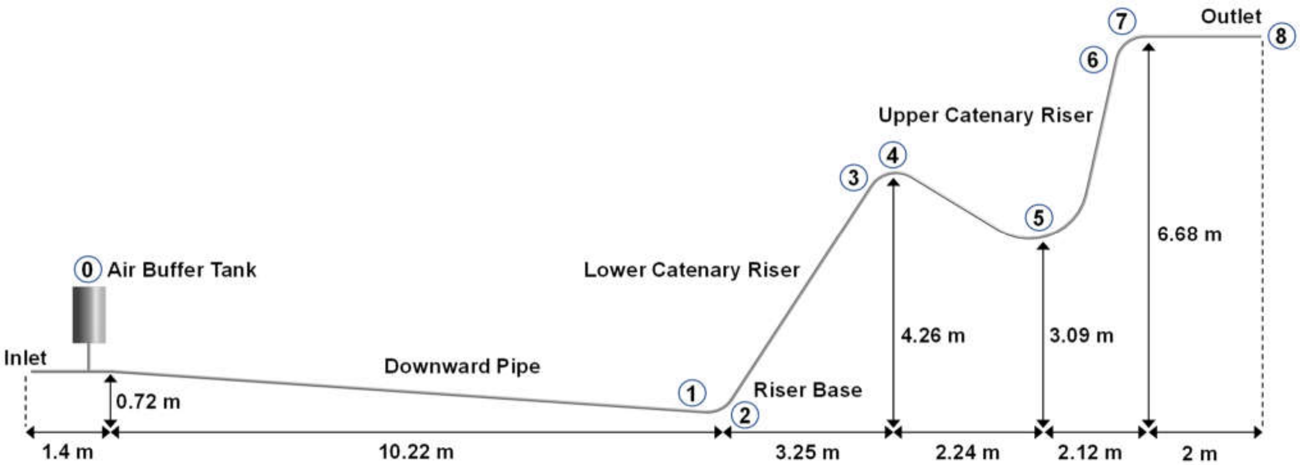


Figure 1. Model geometry and flow monitoring points of an S-shaped riser

accurate performance of the wall boundary, free shear layers, and low Reynolds number flows compared to the k-ε model. The pressure-velocity coupling for the governing equations was performed using the PISO approach. The PRESTO! method for the pressure interpolation was applied for spatial discretization. All numerical schemes are summarized in Table 1.

The total simulation time is about 300s, obtaining more than 5 severe slugging cycles. Simulations were performed within the Newcastle University's Rocket HPC Service and DSME HPC Cluster, using MPI parallel simulations with up to 32 Intel Xeon E5-2699 v4 processors.

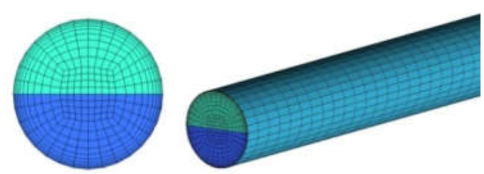
2.1 GEOMETRY AND MESH GENERATOIN

The curved riser geometry for numerical CFD simulations was defined as in Figure 1 based on the study of Park and Nydal [8]. The experiments of air-water flows leading to a severe slugging were carried out through a multiphase loop with a length of 25m and a rigid pipe with an inner diameter of 0.05m.

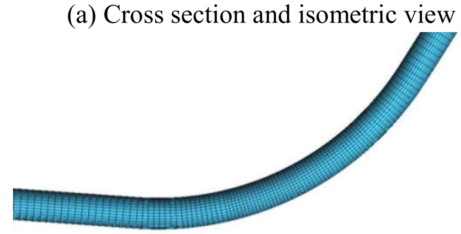
The pipeline-riser system geometrical modeling was generated by using ANSYS Design Modeler. The riser model consists of a horizontal inlet pipeline as a mixing section followed by a downward section with a 10.245m long and an inclination of -2 deg. A bending radius between the downward pipe and the riser section was considered as 10D. The total effective height of the two risers from the S-shape was in 7.85m comprising the height of the 1st and 2nd riser portions of 4.26m and 3.59m, respectively. At the end of the upper riser section, the horizontal pipeline was modeled at the riser top where the two phases flow into the outlet. Both air and water inlet nozzles were provided in the horizontal pipeline. The inlet flows through the horizontally downward pipe and the mixture flow exhibited a stratified flow condition before reaching the riser base.

The gas phase compressibility is a key parameter enabling a severe slugging flow regime. Experiments and simulations were performed by providing an additional buffer tank yielding such compressibility in the pipeline-riser system. This is an effective approach in place of having a long upstream pipeline for sufficient air compression volume. Therefore, an air buffer tank with an inside diameter of 0.57m and a height of 1m was modeled just before the downward section of the horizontal pipeline. Based on a convergence study with the varying buffer tank volume, the tank volume of 0.255m^3, corresponding to a pipe volume of about 130m in length, was found to yield a satisfactory severe slugging in terms of amplitude and cycle.

The computational grid was generated by ANSYS ICEM CFD. The structured hexahedral meshes (e.g. Figure 2), believed to produce an improved efficiency and solution stability over the tetrahedral meshes, were used. A comparative study performed by Biswas and Strawn [21] showed how the hexahedral meshes use computational resources more efficiently at the same level of accuracy. The multi-block O-grid technique was applied to create a hexahedral mesh of pipe volumes. Based on a mesh quality check and grid dependency test, a computational grid of 511,100 hexahedral cells was used in the simulations. Sample results based on 3 setups of hexahedral cells (255,710, 409,265, 511,100) are shown in Figure 3 displaying a similar tendency of the pressure fluctuation at the buffer tank. The surface averaged wall y+ ranges from 10 to 70 throughout the simulation time.



(a) Cross section and isometric view



(b) Side view at the lower riser base

Figure 2. Computational grid and meshing

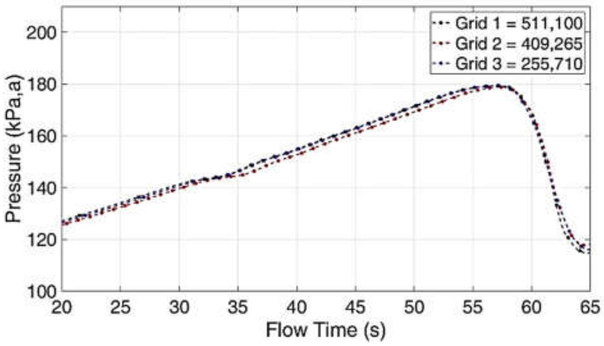


Figure 3. Sample results from a grid dependence check

2.2 INLET AND OPERATING CONDITIONS

Boundary conditions are summarized in Table 2. Gas (air) and liquid (water) were defined as a primary and secondary phase, respectively. A single inlet with a diameter of 50mm and a constant mass flow rate of air (mg) and water (ml) was applied. This corresponds to a superficial gas velocity of 2.02 m/s (Usg) and a superficial liquid velocity of 0.4 m/s (Usl) with a gas/oil ratio of 5. The two-phase flows pass through the horizontal cross section and enters the downstream piping, resulting in a stratified flow. The inlet condition had a turbulence intensity of 5% and a turbulent viscosity ratio of 10. The liquid phase was treated as incompressible, and the gas is considered as a real gas based on the Peng & Robinson Equation of State [22].

Table 2. Summary of Boundary Conditions

Boundary Conditions	Properties
Inlet (Air)	Mass flow inlet = 0.004861842 kg/s Temperature = 288.16K (15 °C) Real gas model: Peng & Robinson E.O.S Viscosity = 1.7894e-05 kg/m-s Molecular Weight = 28.966 kg/mol
Inlet (Water)	Mass flow inlet = 0.783984446 kg/s Temperature = 288.16K (15 °C) Constant density = 998.2 kg/m^3 Viscosity = 0.001003 kg/m-s Molecular weight = 18.0152 kg/kmol
Outlet	Pressure (Constant Atmospheric)
Operating Temperature	288.16K (15 °C)
Operating Pressure	101,325 Pa
Surface Tension	0.0742 N/m
Gravity Acceleration	-9.81 m/s^2 in Y axis
Wall Condition	No slip condition Standard roughness model Roughness height = 2e-06 m Roughness constant = -0.5

2.3 SOLUTION MONITORING

Multiphase flow simulation results were analyzed with respect to the specified monitoring points marked in Figure 1 whose X-Y coordinates are summarized in Table 3.

Table 3. Flow Monitoring Points along Riser

Points	Locations	Coordinates (m)	
		X	Y
0	Air Buffer Tank	1	1.4
1	Riser Bottom Base	11.58	- 0.72
2	Lower Riser Bottom Bend	11.86	-0.67
3	End of Lower Riser	14.4	3.16
4	Pipe Bend (Hog Bend)	14.7	3.5
5	Pipe Bend (Sag Bend)	17.7	2.5
6	End of Upper Riser	18.7	5.5
7	Upper Riser Pipe Bend	18.9	5.8
8	Outlet	19.83	6.68

3. NUMERICAL RESULTS AND DISCUSSION

3.1 FLOW REGIME

The detailed flow patterns at each stage are shown in Figure 4 (as well as in the Appendix) with respect to the contour of the water phase volume fraction. When the stratified flow arrives at the lowest section, the liquid accumulates at the riser base and it blocks the gas phase flow as shown in Figure 4(a). This point can be defined as the beginning of a severe slinging cycle. After this state, the gas pressure upstream of the pipeline and the air buffer tank now begins to increase as the liquid slug increases in length in both the lower riser and pipeline directions.

When the slug front reaches the top end of the lower riser (first catenary riser section) as captured in Figure 4(b), it overflows to the base of the upper riser (second catenary riser section) and then accumulates again at the bend as shown in Figure 4(c). At this moment, the absolute pressure of the riser base is about 144.8 kPa, corresponding to a hydrostatic pressure head of 4.26m equal to the height of the lower riser. However, the gas pressure is still insufficient to overcome the hydrostatic head of the liquid slug in the riser. Therefore, the gas flow is trapped in the upstream pipeline and air buffer tank. As a result, the riser interior is continuously filled with the liquid for a certain period, increasing the hydrostatic pressure.

As the lower catenary riser is fully filled with liquid, the system pressure continues to increase whereas the gas flow passes through the riser in the form of a short strip or bubble shape as shown in Figure 5. This continuous gas penetration causes flow instability and small irregular fluctuations in pressure during the slug generation and production stages. Once the liquid slug reaches the top of the upper catenary riser, it begins the flows out to the outlet, and the lower riser base section experiences the maximum hydrostatic pressure. The gas bubble penetration continues until the gas blowdown stage is initiated. On the other hand, the blocked gas in the upstream pipe now begins to push the filled liquid slug towards the bottom of the riser as the pressure approaches its maximum hydrostatic value. Therefore, the front head of the liquid slug inside the riser is continuously discharged, which is defined as the slug production stage.

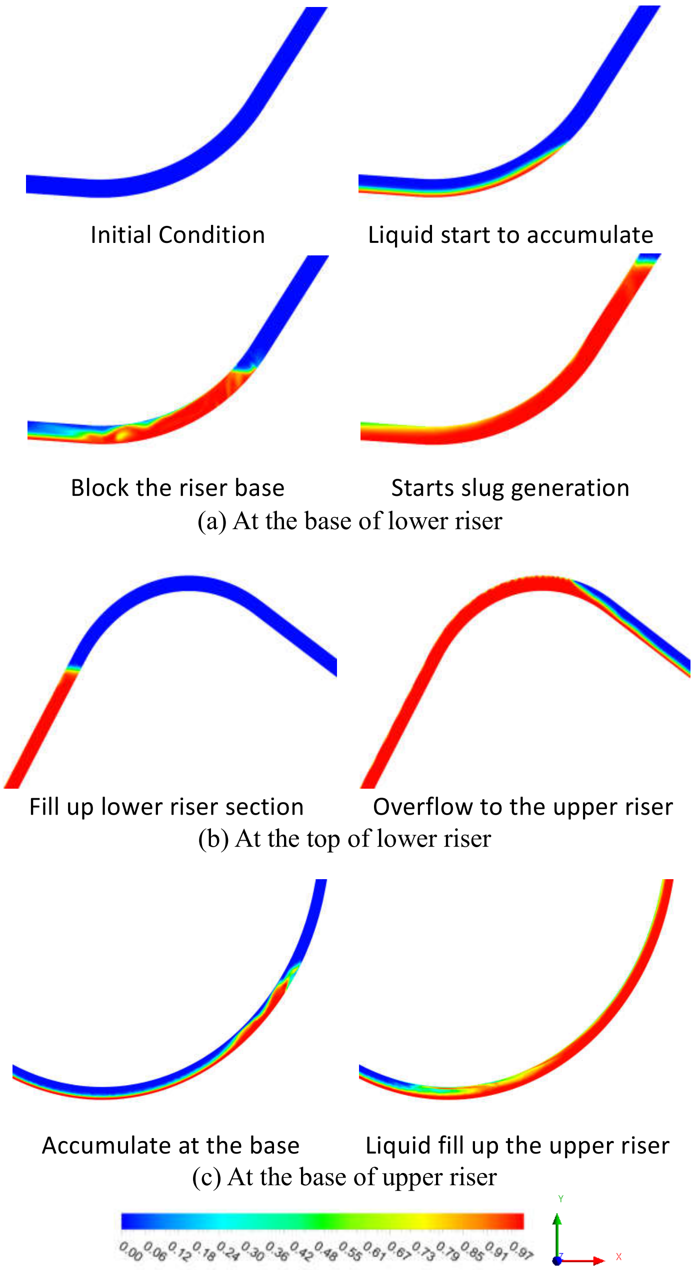


Figure 4. Water volume fraction at (a) lower riser base, (b) top bend of lower riser and (c) base of upper riser

Figure 6 displays the flow regime of each time instant during the severe slugging cycle in a plan view of the water volume fraction. After a significant amount of bubbles have passed along the riser sections, and the upstream pressurized gas arrives at the riser bottom bend, the gas now expands and discharges very quickly in the outlet direction.

The severe slugging flow phenomenon is basically due to the gas compressibility. The pressurized gas in the upstream pipe provides a flow momentum energy for a blowout. The liquid slug, filling riser sections, is then quickly pushed out to the discharge, and some liquid flows travel along the pipe wall in the form of a thin film. Along with the expansion of the gas in this process, a very rapid pressure reduction occurs throughout the entire pipe-riser system. An evolution of the water volume fraction is illustrated in Figures 7 (along riser) and 8 (per cross sections), during the gas blowdown stage.

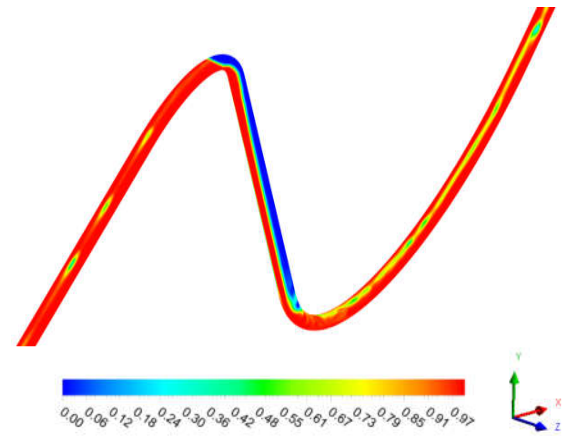


Figure 5. Water volume fraction showing a bubble penetration in ISO View

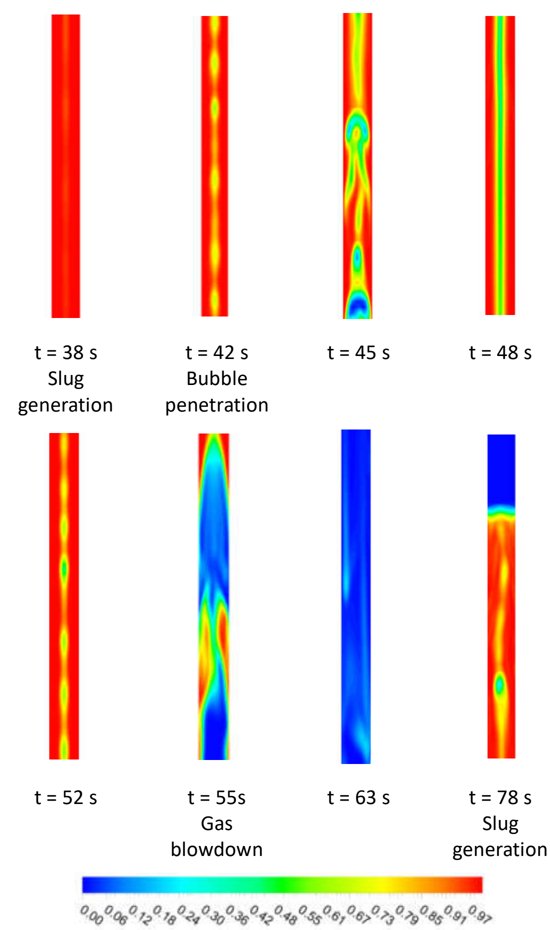


Figure 6. Plan view of severe slugging process

A blowdown stage lasts until the system pressure reaches a minimum value at which the gas phase cannot have enough speed and momentum to support the liquid flow. Then, the liquid film on the riser wall begins to fall back to each riser base (e.g. in Figure 9). The riser base is blocked with the fallen liquid and the gas flow is blocked again. As pressure begins to rise, the next cycle begins and overall steps repeat.

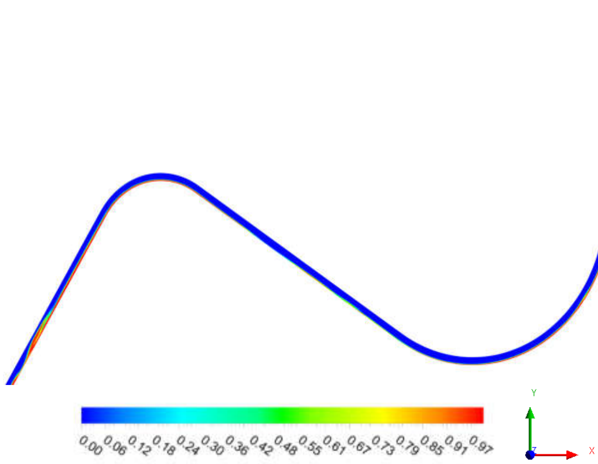
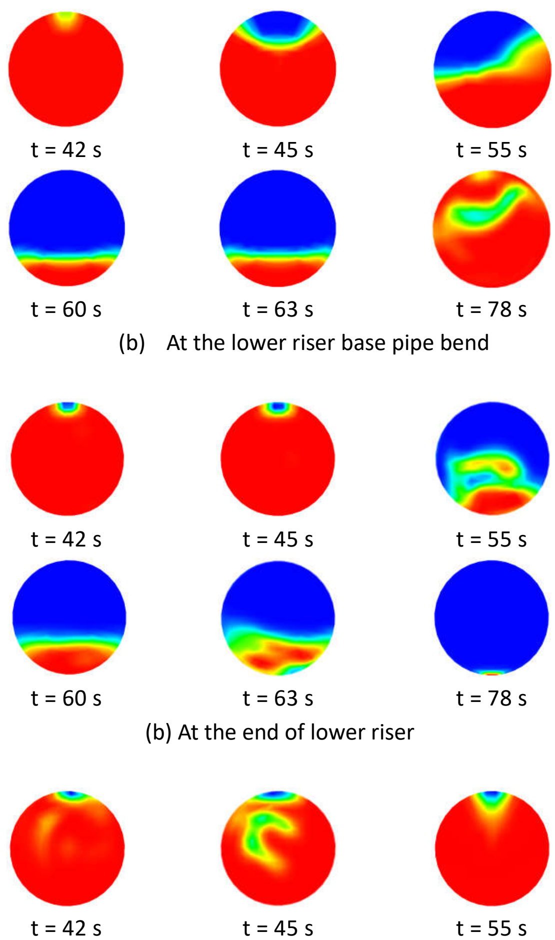


Figure 7. Volume fraction of water during gas blowdown



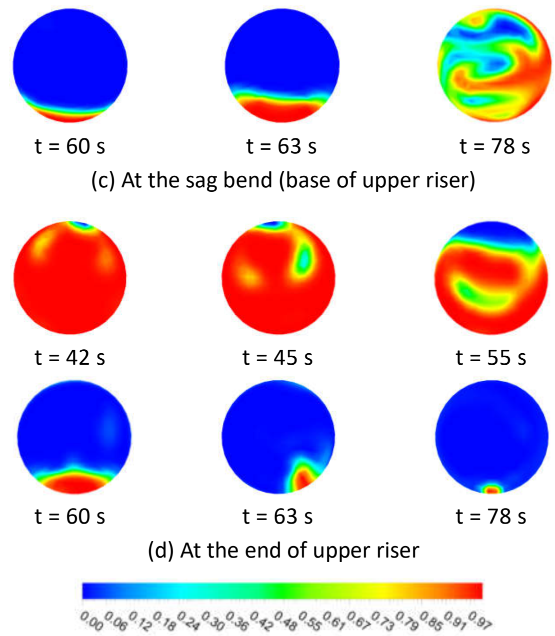


Figure 8. Cross-sectional view of water volume fraction during gas blowdown stage

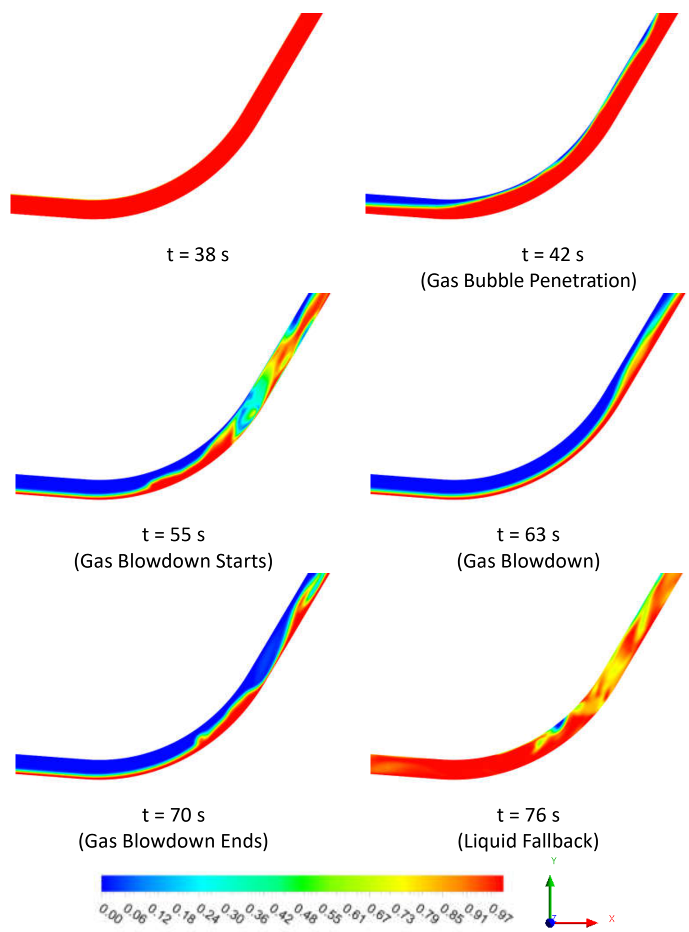


Figure 9. Volume fraction at riser base during bubble penetration and gas blowdown stage

3.2 PRESSURE FLUCTUATION

Simulation results also reveal the continuous cyclic pressure fluctuations in the riser system. This represents a typical scenario of the severe slugging II (SS-II) with a short peak pressure just before starting the gas blowdown stage without a long slug production phase at a constant maximum pressure.

In Figure 10, the pressure amplitude at the riser base and bottom bend is repeated more than 6 times for a period of about 45s for the recorded 300s simulation time. The maximum and minimum absolute pressure (denoted by 'a' in the vertical-axis units of Figures 3, 10, 11) values are 180 kPa and 120 kPa, respectively. The sections of the lower catenary riser bases show the highest pressure of the severe slugging cycle process.

The pressure curves measured at other monitoring points also indicate a repetitive pattern. It is seen that the middle portions of the riser system (monitoring point 3, 4 and 5) have relatively lower maximum and minimum pressure than that of the lower riser base. The outlet section appears to have a certain amount of pressure only at the gas blowdown stage, because the operating condition is set at the atmospheric pressure.

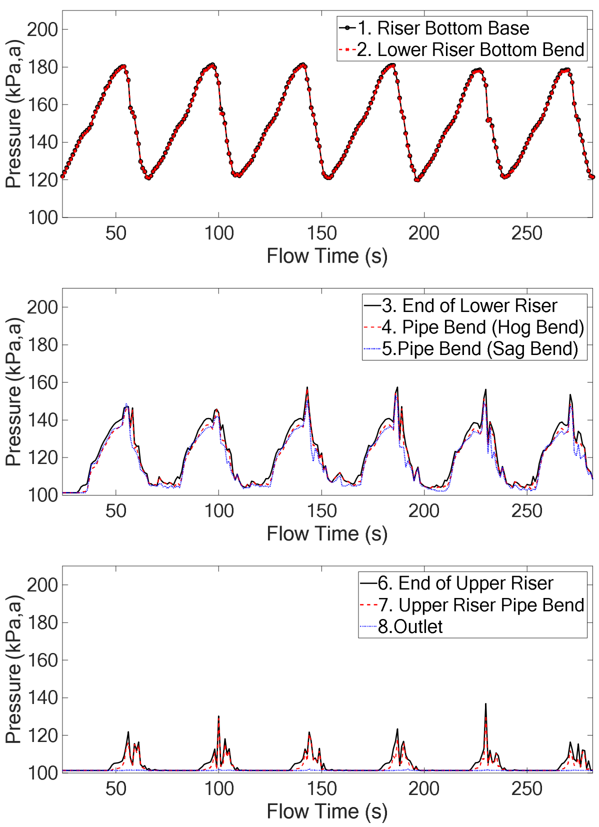


Figure 10. Pressure time histories at monitoring points

Based on the experiments performed by Park and Nydal [8] and their OLGA simulations, the pressures of the air buffer tanks is compared in Figure 11. It is noticed that a fluctuation period from the CFD analysis is relatively shorter, but the magnitude of the pressure amplitude is almost the same as the experiment. Such a difference in the pressure period might be due to that there are some differences in the boundary conditions between the experiment and the simulation, apart from other factors such as measurement and post-processing of data.

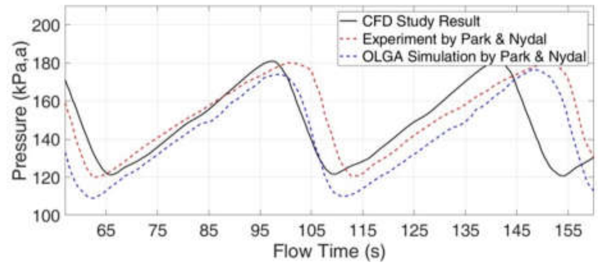


Figure 11. Comparison of pressure time histories

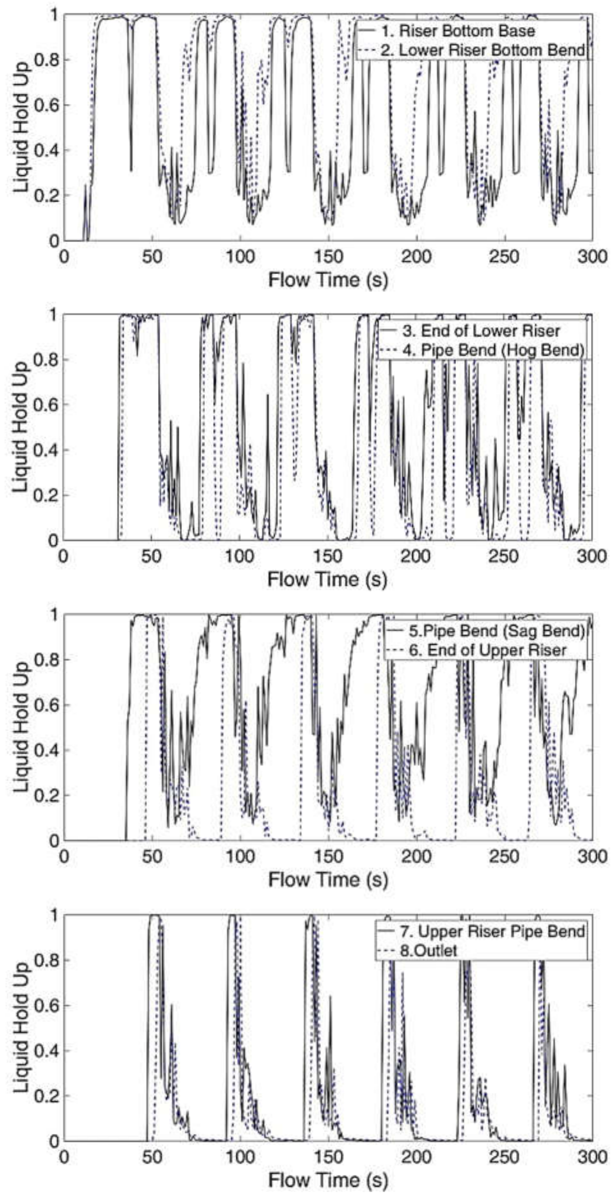


Figure 12. Time histories of liquid holdup

3.3 LIQUID HOLDUP

A liquid holdup is an important criterion for the identification of a severe slugging flow regime. The surface area averaged volume fraction at each monitoring point is recorded during the simulation to examine the flow behaviors. In Figure 12, the liquid holdup time histories at the monitoring points are presented, revealing a repetitive pattern similar to the pressure time histories. This output illustrates the correspondence with the pressure fluctuation within each severe slugging cycle. The monitoring points show the same tendency in which the slug production stage has a liquid volume fraction close to 1 and a sharp drop below 0.5 during the gas blow down period.

The irregular responses in some periods are mainly due to the gas bubble penetration. It confirms that both liquid holdup and pressure values are affected by the gas bubble penetration. In particular, the upper riser top bend and the discharge outlet (monitoring points 7, 8) have a liquid hold up value only during the slug production and gas blowdown phases as there is no liquid present in other severe slugging stages.

3.4 MIXTURE VELOCITY MAGNITUDE

The mixture velocities at all monitoring points have similar magnitude and time variation trends. The maximum velocity occurs in the middle of the gas blowdown stage as shown in Figure 13. This is because the compressed air is released very quickly through the riser outlet. Therefore, the magnitude of the velocity is proportional to the maximum pressure of the system.

At the end of each slugging cycle, the flow velocity decreases as the gas exits the outlet and the pressure decreases. As a result, the flow momentum is insufficient to push the slug flow to the outlet, causing the liquid part on the pipe wall side begin to drop to the lower point.

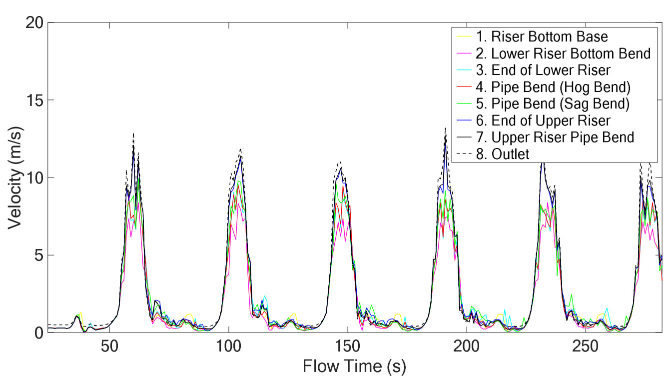


Figure 13. Time histories of mixture velocities

4. CONCLUSIONS

3-D numerical simulations of the severe liquid-gas slugging in an S-shaped riser have been performed based on the finite volume method and validated by experimental results. The main observations are summarized as follows.

- A severe slugging phenomenon has been captured, exhibiting the repetitive pressure fluctuations due to the liquid slug accumulation and gas compressibility. Different flow patterns in different slugging stages are identified and analyzed. The present 3-D simulations show a qualitative trend consistent with experimental results reported by the literature [8].
- The severe slugging, with the characteristics of starting the gas blowdown stage after the relatively short slug generation and slug production, is noticed. Therefore, it is defined to be in the SS-II category for this S-shaped riser. The transitional slugging indicates that the slug length is shorter than the total riser length, together with the multiple gas bubble penetrations occurring over the slugging cycle.
- The mixture velocities and liquid holdups during the slugging cycle are also investigated. A complex flow pattern occurs when the high velocity mixture passes through the riser system. A peak velocity during the gas blowdown is remarked.

ACKNOWLEDGMENTS

This research is supported by PNU Korea-UK Global Program in Offshore Engineering (N0001288) funded by the Ministry of Trade, Industry and Energy. N Srinil thanks the funding support from the Engineering and Physical Sciences Research Council, UK, for the MUFFINS project (EP/P033148/1).

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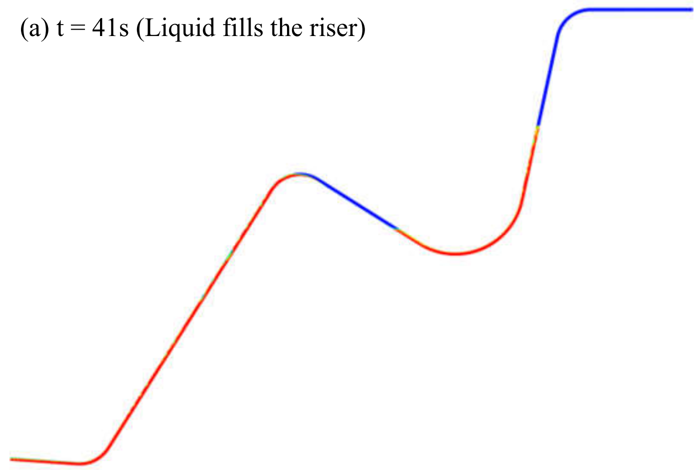
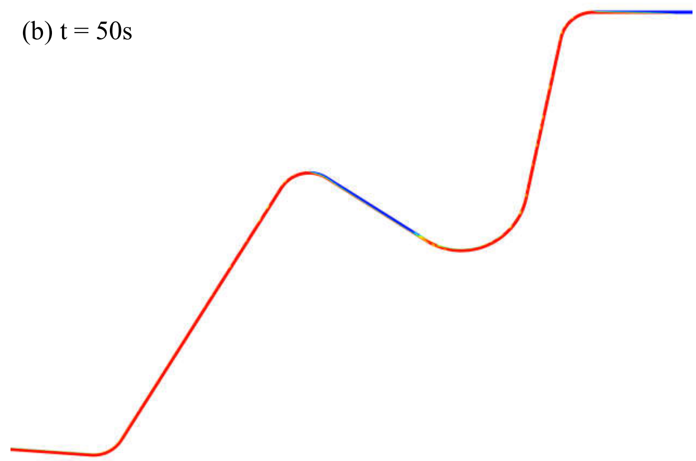
Appendix: Illustration of liquid-gas flow patterns during a severe slugging at the selected time instants along S-shaped riser

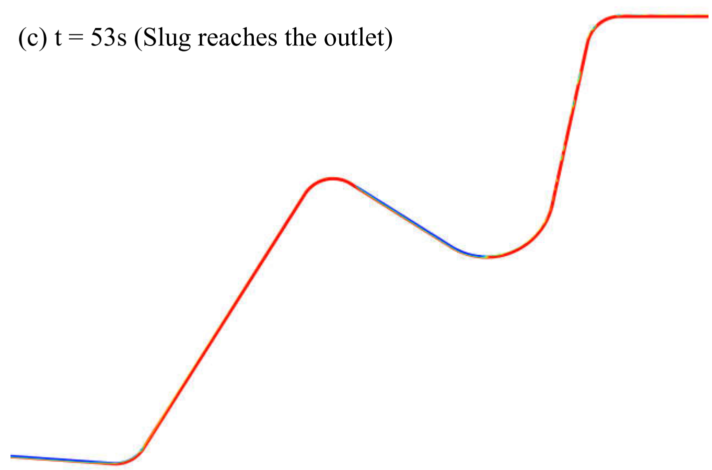
(a) t = 41s (Liquid fills the riser)

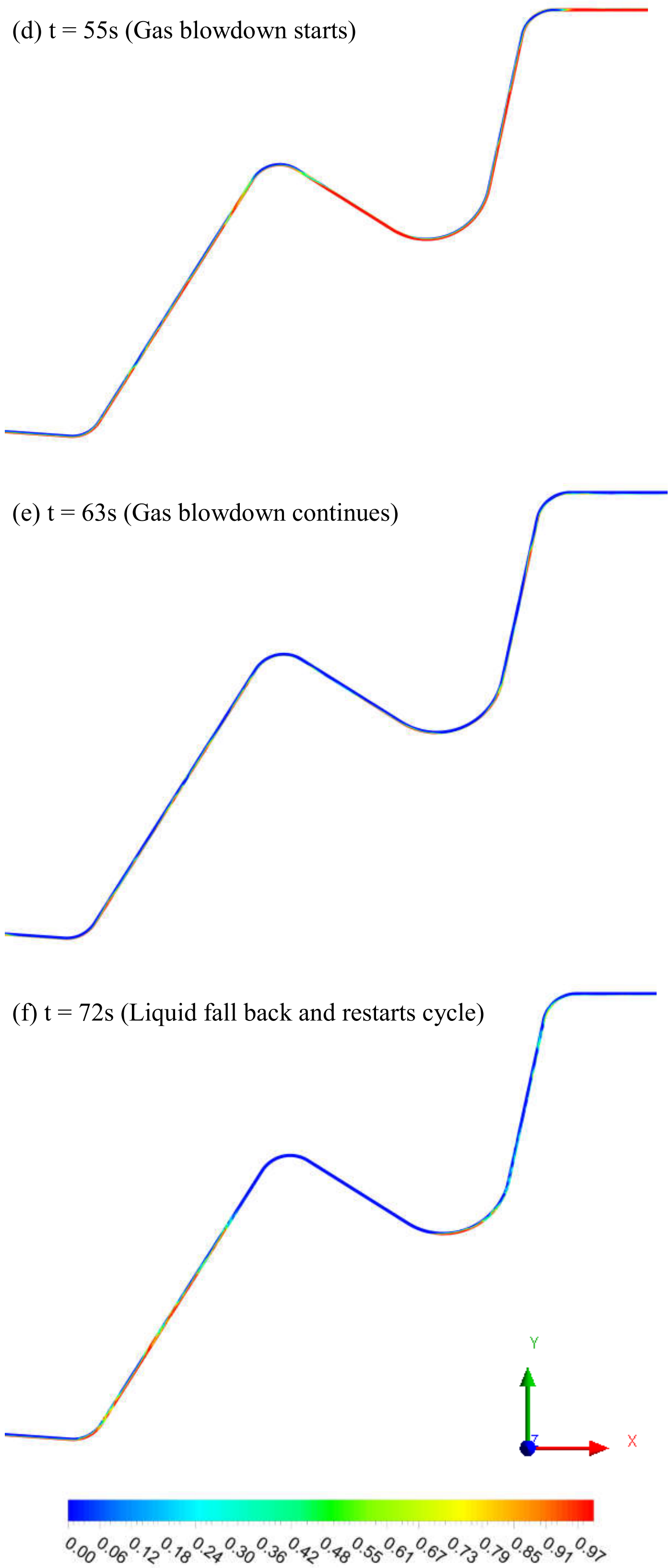


(b) t = 50s



(c) t = 53s (Slug reaches the outlet)





Liquid phase fraction along S-shaped riser